

# Understanding sensitivity of retention programs to wet end chemical contamination in TMP-based newsprint furnish

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## SUMMARY

In this paper, the effect of conductivity and cationic demand on the drainage properties of a model TMP-based newsprint furnish was studied. Free drainage was measured at two pH values, 5 and 7, as a function of concentration of several different ions. These measurements were conducted for several typical retention programs used in newsprint applications. Results are discussed in terms of an impact of individual ions and in terms of the general impact of conductivity and cationic demand on drainage.

## Keywords

Thermomechanical pulp, drainage, retention, conductivity, cationic demand, flocculant, bleaching, contamination, mill closure, bentonite, polyacrylamide, polyethylene oxide

Increased closure of water systems, more aggressive bleaching processes, higher de-inked pulp content, and higher shear forming sections of new and modern paper machines result in increased levels of contamination of the paper machine wet end. The degree of expected build-up of detrimental substances as a result of increased degree of closure has been discussed by several authors (1,2,3,4,5). Problems related to the accumulation of these substances were grouped into the following basic categories: deposits affecting quality and runnability, interference with the inter-fiber bonding and resulting strength losses and lower efficiency of chemical additives.

Newsprint grades, or in a broader sense, any grades based on mechanical pulps, represent systems with the highest variability of conditions affecting overall performance of the wet-end of the paper machine. Differences between machines

require that the process of selection of a retention program for any specific application includes screening a large number of retention polymers. For any specific machine, variation of conditions results in unstable performance of wet end operations and affects negatively both the efficiency of the machine and the quality of the product.

Detrimental substances that accumulate in the paper machine water system can be divided into two groups - simple salts and anionic, polymeric or oligomeric substances. Accumulation of simple salts leads to an increased ionic strength or conductivity of the system. Salts have very little affinity for the formed web of paper and the degree of their accumulation is closely related to the degree of closure of machine water circuits. Anionic polymeric substances increase cationic demand of the system due to their ability to interact with cationic polymers. Several authors have discussed mechanisms of deactivation of cationic additives by detrimental substances (6,7,8,9,10).

Hydrogen peroxide bleached mechanical pulps are known for unusually high levels of cationic demand. At first, this was mostly attributed to the use of sodium silicate and products of its hydrolysis and polymerization (11,12,13,14,15,16). Recently, Thornton identified organic polymeric species, polygalacturonic acids, responsible for a significant portion of a total cationic demand and generated during peroxide bleaching of mechanical pulps (17,18).

The mechanism of action of retention polymers includes an adsorption step, followed by fines aggregation and their hetero-aggregation with fibres (19,20,21,22,23,24). Electrostatic interaction is the most important driving force leading to adsorption of cationic polymer. Other forces may be responsible for adsorption of anionic and non-ionic retention polymers. Mechanisms that operate following the original adsorption of the polymer and lead to aggregation include

charge neutralization, patch or mosaic adhesion and the most powerful, polymer bridging.

Most often used retention programs in mechanical grades include high molecular weight flocculants applied alone or in combination with alum, coagulants, and microparticles. Most typically, a cationic flocculant is applied, although programs utilizing slightly anionic flocculants, especially in combination with bentonite or alum, and non-ionic polyethylene oxide (PEO) are also applied. Intermediate molecular weight cationic polymers, occupying a position between coagulants and flocculants called Hybrids, were introduced in Canada (25) and found many applications in mechanical grades.

From the chemical point of view the most important factors that influence the wet-end of paper machines are:

- pH - controls the degree of ionization of acidic functions in the system and contributes to the charge development of furnish elements and some of the additives
- Conductivity - being a measure of the concentration of simple ions in the system, it determines conformation and consequently, performance of charged (cationic or anionic) flocculants.
- Cationic demand - measures total capacity of furnish elements to neutralize cationic polymers.
- Extractive level and type - this factor indicates propensity of the system to experience deposits on the machine.
- Hardness -  $\text{Ca}^{+2}$  and  $\text{Mg}^{+2}$  ion concentration, impacts deposit formation via interaction with fatty or resin acid soaps and precipitation of Ca salts.

There have been several papers published recently and reviewed below that discuss the impact of chemical variables on the activity of retention aids. Retention programs provide increased incorporation of small particles into the structure of the formed web of paper (retention), increase the rate of removal of water in the forming

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Wu's Harmonic Mean approach give predictions that are in better agreement with results obtained using other techniques, than does the Good van Oss approach.

Cationic surfactants and polymers adsorb onto the non-image area of the plate, leading to changes of the surface energetic characteristics. Cationic polymer also causes topographical change of the non-image area of the plate. The changes in surface energy caused by anionic surfactants are small; suggesting that adsorption of the anionic surfactant on the non-image area is weaker than that of cationic substances.

Whereas the adsorption of cationic surfactants has been reported to cause printing problems, this study further shows that the adsorption of cationic polymers can also cause scumming (printing from the non-image area of plate), even though they are not surfactants. These compounds, in the form of free molecules, should be kept away from the printing system.

## ACKNOWLEDGEMENTS

This work was carried out as part of the research program for the CRC Smartprint Funding received from the Federal Government and Norske-Skog via the Smartprint CRC program is gratefully acknowledged.

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Original manuscript received 13 Aug 2004, revision accepted 16 March 2005

section (drainage) and provide increased rate of removal of detrimental substances (deposit control). These three aspects are not quite independent and are also closely related to the fourth – formation. It may not always be proper to define performance of a polymer based solely on retention activity. The selected retention polymer has to provide a specific blend of performance in terms of retention, drainage, deposit control, formation and cost.

Dobbins and Alexander (26) reported on a pilot machine study showing the impact of increased mill water closure on machine operation and paper quality. Davison (27) studied an effect of pH, ionic strength, calcium ion, and alum anionic contaminants on the retention of fines and filler using a mixture of HWK and SWK (3:1). Both anionic and cationic retention polymers were negatively affected by increased concentrations of either  $\text{Na}_2\text{SO}_4$  or NaCl. Conductivity of the system was modified between 200 and 3000  $\mu\text{S}/\text{cm}$  and an average drop in observed retention level of 5-18% at the same polymer dosage, was observed for various products. Adding alum could, to a large extent, control the negative effect of the addition of sodium lignosulfonate on cationic retention polymer.

Lindstrom and Wagberg (28) studied adsorption of cationic polyacrylamide polymers onto the surface of bleached SWK pulp at different levels of simple electrolytes (NaCl,  $\text{CaCl}_2$  and  $\text{Na}_2\text{SO}_4$ ). Buontempo, Sherman and St. John (29) used the Britt Jar technique to study the effect of ionic species on performance of cationic flocculants with different charge density. It was found that, at a low starch addition level, all studied flocculants retained a high level of performance when conductivity was changed between 45 and 3000  $\mu\text{S}/\text{cm}$ . For furnish containing starch, all studied flocculants showed a marked decrease in performance. For close to 25 years, polyethylene oxide, PEO has been known in practice and widely studied as a retention program in the laboratory. PEO is a non-ionic polymer that operates via bridging flocculation. In most of the systems it requires pre-addition of a cofactor, typically phenol formaldehyde resin or other polyphenolic material. PEO based programs often show strong performance in terms of flocculation that may lead to formation problems. Additionally, shear and chemical sensitivity contribute to its limited number of applications.

Recently there has been significant activity in publications regarding mill closure and water contamination that included comparative studies of cofactor-PEO, and cationic flocculant based retention programs (30,31,32,33,34,35,36,37). Although all of these publications generally point toward higher resistance of PEO-based programs in systems with elevated levels of conductivity and cationic demand, they differ in specific conclusions.

Miyaniishi et.al. (34) reported that increasing levels of conductivity in wood-containing grades had little effect on the performance of cationic polymers (single, dual and microparticle programs). Increased cationic demand (added Kraft lignin), on the other hand, resulted in decreased activity of cationic flocculants. Hulkko and Deng (30), Allen et.al. (31,36,37) and Englezos (35) reported negative impact of both conductivity and cationic demand on retention programs using cationic polymers. Use of FPR measurement allowing matt formation (31,37) results in high contribution of filtration component to recorded retention values (FPR in excess of 80%) and reduces the range of differentiation between applied retention programs. Additionally, dosages of retention polymers of up to 1% (10 kg/t) (31) based on active polymer, by far exceed typical dosages (in the range of 200-500 g/t). If analysis of results was limited to a more practical dosage range, such conclusions would be much more difficult to make.

The objective of this investigation is to determine the degree of sensitivity of different retention programs to varying levels of many contaminants in TMP furnish. Simple free drainage measurement was selected as a measured response and sufficient experiments were conducted to ensure statistical validity of this work.

## MATERIALS AND METHODS

### Sample preparation

TMP pulp (thick stock) was collected from the mill and stored in the refrigerator for the duration of the project. The appropriate amount of pulp was diluted with tap water to provide final consistency of about 0.35%. A sample of this furnish was collected for hardness measurement before it was split into two parts that had their pH adjusted to 5 and 7 respectively, using  $\text{H}_2\text{SO}_4$  and NaOH. Both these samples were then split into five equal parts, and appropriate amounts of

contaminant were added to each, just before testing. Cationic demand, conductivity, freeness, acidity, alkalinity, and pH were then measured for each of the samples to ensure control of the sample preparation and to allow for additional interpretation of results.

The same thick stock sample was used throughout the duration of this project. Cationic demand, alkalinity consistency, hardness, freeness and conductivity of the original 'clean' sample of the stock at pH=5, were checked before each series of experiments and these showed no substantial change over initial sample properties.

### Contaminants studied

The following contaminants were used in our work – maximum dosage (ppm) is shown in brackets: sulphate  $\text{SO}_4^{2-}$  (10000), sulphite  $\text{SO}_3^{2-}$  (1000), phosphate  $\text{PO}_4^{3-}$  (200), chloride  $\text{Cl}^-$  (10000), borates (500), silicate (1000), lignosulfonate (1000), EDTA (1000), DTPA (1000). Sodium salts of analytical purity were used. Addition of individual salts was based on stoichiometric calculations and was always confirmed analytically using appropriate Hach DR200 method. In order to ensure the concentration of salt remained constant throughout the entire set of experiments, kinetics of adsorption was first studied for sulphate ion. This study showed that the concentration of sulphate ion in solution did not change within 1 hour – time required to complete a full set of drainage experiments for all retention programs at a given contaminant concentration level.

### Retention programs studied

Retention programs studied in our work included:

- single, high charge density cationic polymer program (HCF) using polyacrylamide copolymer with 20 mole% of methyl chloride quarternized dimethylaminoethyl acrylate. Dosages used in this paper are calculated based on commercial product (about 35% of active solids).
- dual polymer program using EPI/DMA coagulant (C) in combination with HCF
- HCF program followed by addition of bentonite
- Cofactor (phenol formaldehyde resin-PFR)-PEO program

Solutions of retention polymers were prepared fresh daily.

**Drainage experiment**

The Nalco-developed Alchem Drainage Tester was used to measure the drainage rates. This tester consists of a Plexiglas tube with a diameter of about 10 cm equipped at the top with a sample delivery container with a stopper, series of plastic baffles and 70 mesh screen at the bottom. The sample is delivered at the top, and after opening the stopper; the volume of water collected after a pre-set time is measured. In these experiments the time was set to 5 seconds. (Measurements with an Alchem Drainage tester give results that typically correlate well with freeness measurements and represent free drainage of the stock.)

A typical, baffled Britt Jar was used to treat the sample before each drainage experiment. The bottom screen in the jar was substituted with a plastic screen to ensure controlled sample volume and consistency. The Britt Jar impeller was always set for 1000 rpm. Twenty sec. experiments were conducted with the following addition sequence of chemicals:

- start impeller
- 0 sec-add 500 ml sample
- 5 sec-add coagulant
- 10 sec-add flocculant
- 15 sec-add microparticle
- 20 sec-stop impeller and transfer sample to the Alchem Drainage tester.

The drainage experiment was performed immediately to avoid solids separation, and the volume of the sample collected during 5 seconds was then measured.

**Presentation of results**

For each contaminant under investigation, the drainage for freshly prepared, uncontaminated (no contaminant added) sample

was measured without ( $V_{00}$ ) and with chemical treatment ( $V_{0t}$ ). The difference,  $\Delta V_{0t} = V_{0t} - V_{00}$  represents the drainage improvement offered by particular chemical treatment for uncontaminated 'clean' sample of furnish. After drainage was measured for the particular contaminant level ( $V_{ct}$ ), the residual drainage improvement above untreated sample for this contamination level can be calculated as  $\Delta V_{ct} = V_{ct} - V_{00}$ . Loss of the drainage rate due to the contaminant addition ( $D_{var}$ ) is then calculated as:

$$D_{var}(\%) = \left( \frac{\Delta V_{ct}}{\Delta V_{0t}} \right) * 100$$

Each experiment was duplicated and the mean value of drainage was used in further analysis. Following this procedure contaminant level versus  $D_{var}(\%)$  curves were obtained for each contaminant at two pH ranges (5 and 7), for several different retention programs each at 2 dosage levels. Results were then tabulated and analyzed in terms of an impact of contaminant concentration on reduction in free drainage rate.

**RESULTS AND DISCUSSION**

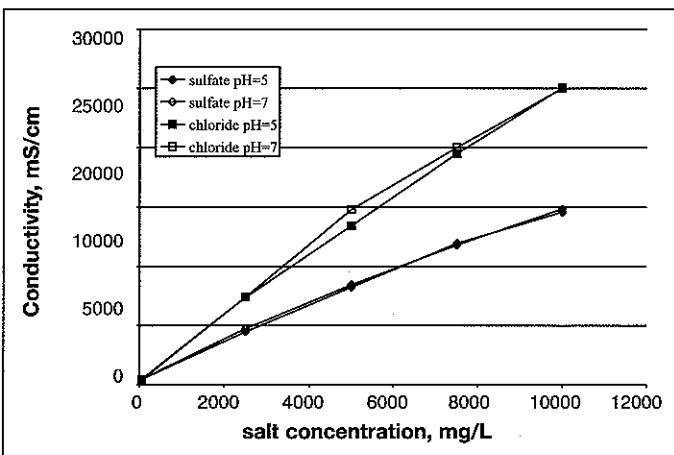
The objective of this study was to establish sensitivity of selected programs to changes in chemical environment rather than actual performance level. Therefore, it is possible that a program that shows higher loss of the performance still remains more active than a less sensitive program.

Results are presented in the form of graphs representing loss of the drainage  $D_{var}(\%)$  as a function of the concentration of contaminant in ppm. For all drainage experiments, samples were fully characterized in terms of pH, conductivity,

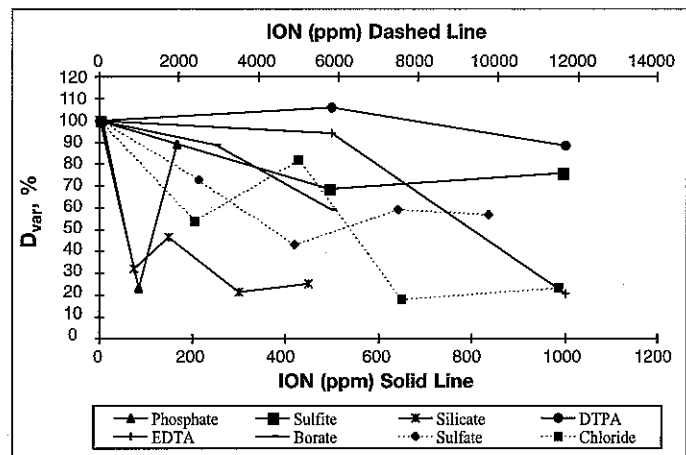
cationic demand, and calcium ion concentration. There are many ways to analyze this very large body of data. In this paper we concentrate on the simple, empirical relationship between the level of contaminant and resulting loss of drainage rate. To allow for the comparison of our results with other studies dealing with more general impact of salts on retention polymers, Figure 1 presents the relationship between concentrations of NaCl and  $Na_2SO_4$  and conductivity values.

Ranges of concentrations selected for various contaminants differ significantly. For sulfate and chloride, that serve as model ionic contaminants, maximum dosage reaches a level of 10000 ppm. For other contaminants this maximum dosage does not exceed 1000 ppm. In order to present results in a compact manner we use a secondary x axis with a clear indication of axes used for individual contaminant. Sulfates and chlorides were selected as model ionic strength modifiers because they do not undergo hydrolysis and do not change their form with system pH. Phosphate, silicate, borate, carboxylates, and sulfites all are derived from weak acids and undergo hydrolysis that depends on system pH. Therefore, their impact on the retention polymers has to be treated in a more empirical way. Detailed analysis in terms of identifying the mechanism of their impact would require detailed knowledge of the form existing under given conditions and would therefore require significant additional work.

Figures 2-5 represent data collected for single polymer, high charge density flocculant (HCF), and for dual polymer program, coagulant – high charge density flocculant (C-HCF), at pH=5 and 7.



**Fig. 1** Relationship between concentration of sodium chloride and sodium sulfate and conductivity.



**Fig. 2**  $D_{var}(\%)$  for single polymer program HCF (HCF at 2kg/t) at pH=5.

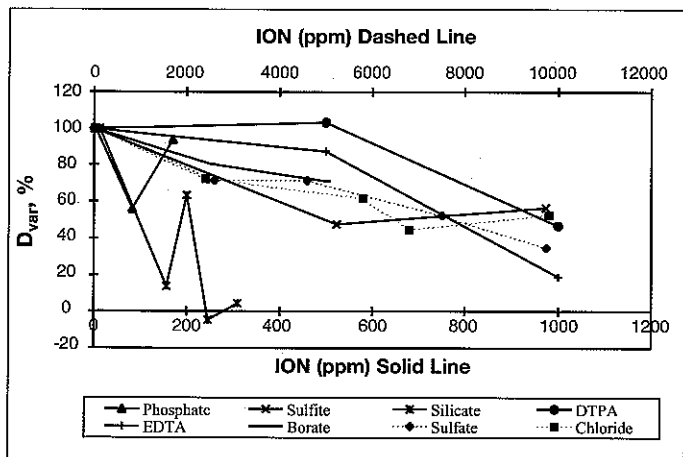


Fig. 3  $D_{var}$  (%) for single polymer program HCF (HCF at 2 kg/t) at pH=7.

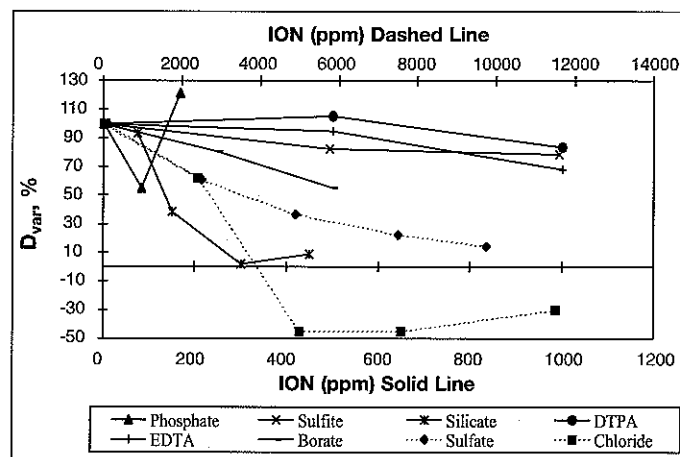


Fig. 4  $D_{var}$  (%) for dual polymer program (C at 2 kg/t and HCF at 2 kg/t) at pH=5.

Data presented in this work represent only lower dosages used in the study (3 kg/t for HCF in a single polymer program and 2 kg/t for C with 2 kg/t for HCF in the dual polymer program).

A higher range of polymer addition rates was also studied and general trends were very similar. Single cationic polymer (HCF) and dual polymer program based on this flocculant (C-HCF) are affected by increased levels of ionic substances. These types of programs are often used in the production of mechanical grades. These programs are affected by the presence of chlorides and sulfates. Effects of these ions seem to be related to increased conductivity of the system. Conductivity of the samples dosed with NaCl and Na<sub>2</sub>SO<sub>4</sub> changed between 460-25,000 and 460-15,000, respectively, when concentration of each ion reaches 10,000 ppm. At pH=5, the single cationic polymer program at the highest chloride and sulfate concentrations loses about 70% of its 'clean' system performance.

The dual polymer program (C-HCF) at

pH=5 offered a better performance in the clean system but was even more affected by increasing levels of chlorides and sulfates. Chlorides seem to be significantly more detrimental and already at the level of 5000 ppm, the drainage gain from chemical treatment in 'clean' sample is fully lost. Sulfates at the same addition level reduce performance observed in the clean system by the dual polymer program by about 70%.

At pH=7 (Fig.3), a single polymer program loses about 50% of HCF performance at the highest dosages of chloride and sulfate ions. Therefore, it seems that the detrimental effect of both ions is slightly lower in pH=7 than in pH=5. This effect was observed at two levels of the flocculant concentration (2 and 3 kg/t). The difference between detrimental character of chloride and sulfates observed at pH=7 is much lower, but still clearly visible, especially at higher concentration ranges.

Several earlier studies specifically discussed effects of sulfates on retention flocculants (28,38,39). The balance of the

following effects-compression of the diffuse double layer, varied adsorption properties of the polymer, changes in the conformation of the polymer and its ability to bridge, determines net effect of salt addition.

Lindstrom and Wagberg (28) also observed significant differences in the effect of sulfates and chlorides on adsorption of cationic polyacrylamides that could support our observations.

Silicates as expected are very detrimental to both single cationic flocculant and dual polymer programs. Their effect is based mainly on their ability to form complexes with cationic polymers. Phosphates exhibit very specific effects with an initial decrease followed by an increase of drainage that is consistently observed throughout all our work. Other ions like borates, sulfites and both chelants, EDTA and DTPA, show significantly lower impact on the drainage, especially for dual polymer programs.

Addition of bentonite following HCF does not improve overall stability of such programs significantly. Figures 6 and 7

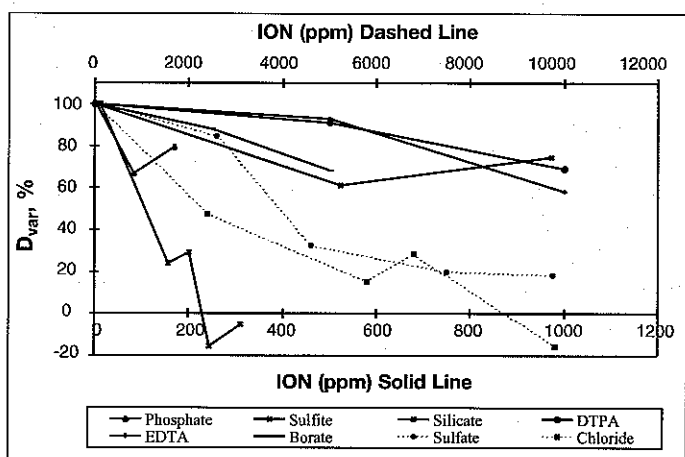


Fig. 5  $D_{var}$  (%) for dual polymer program (C at 2 kg/t and HCF at 2 kg/t) at pH=7.

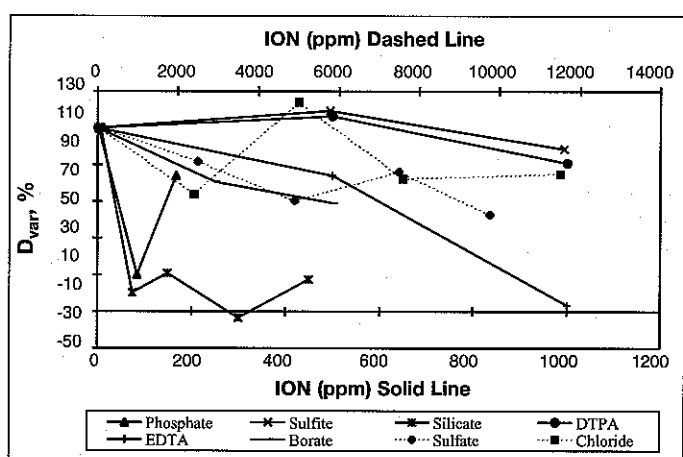


Fig. 6  $D_{var}$  (%) for HCF (at 2 kg/t) and bentonite (6 kg/t) at pH=5.

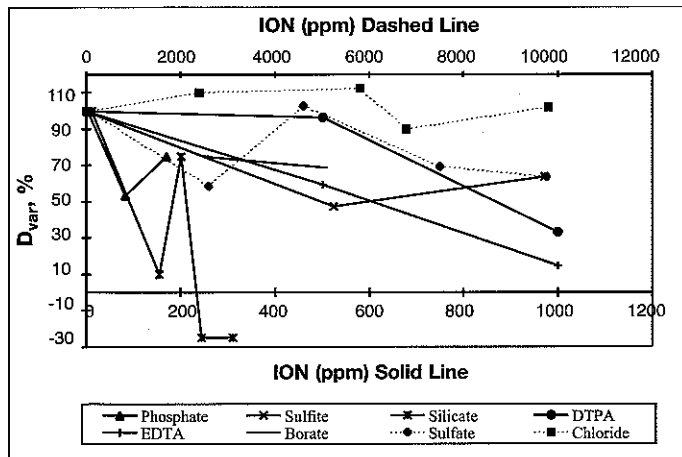


Fig. 7  $D_{var}$  (%) for HCF (at 2 kg/t) and bentonite (6 kg/t) at pH=7.

show results observed for the program based on HCF and bentonite at 6 kg/t at pH=5 and 7, respectively. The negative impact of sulfate and chloride addition is reduced compared to single and dual polymer programs based on the same flocculant. On the other hand, the negative impact of silicates is even stronger than for other programs. It also seems that the impact of EDTA is higher than for the programs discussed earlier. Although bentonite has been used in papermaking for at least 40 years, the mechanism of its action is not yet fully understood. Several possible mechanisms were proposed by Lindstrom, who suggested formation of a network between bentonite and polyacrylamide polymer molecule that decreases solubility of polymer, increases its adsorption and allows for sweeping of colloidal particles from the water phase (40). Bentonite forms platelets with two dimensions in the  $\mu\text{m}$  range, comparable with the length of high molecular weight polymer in solution. It is quite possible that bentonite contributes to the bridging mechanism of flocculation. This is further possible because bentonite platelets are negatively charged on the faces and positively on the edges. By contributing to bridging, bentonite would, to some extent, reduce sensitivity of the system to conductivity, as it would not undergo conformational changes (coiling) that typically reduce effectiveness of synthetic polymers. Bentonite will still remain sensitive to changes in the diffuse double layer thickness and surface properties that lead to variation in adsorption properties. Higher sensitivity to silicate and chelant levels may be a reflection of some sort of interaction with the metal ions on the surface of the bentonite platelet that

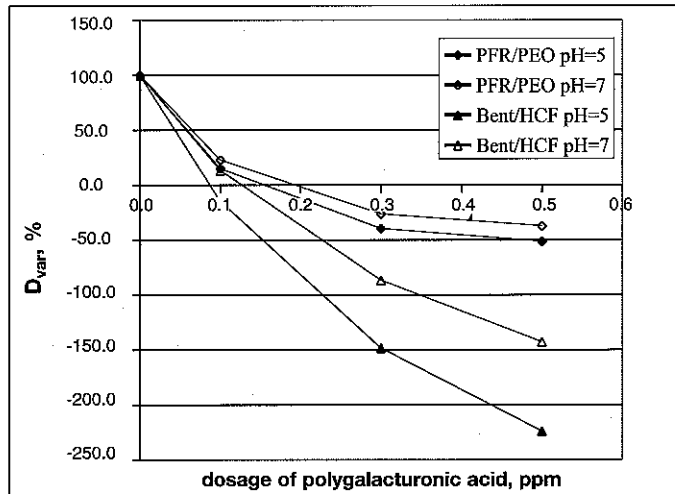


Fig. 8 Impact of added polygalacturonic acid (g/L) on the drainage of PFR/PEO and HCF/bentonite programs.

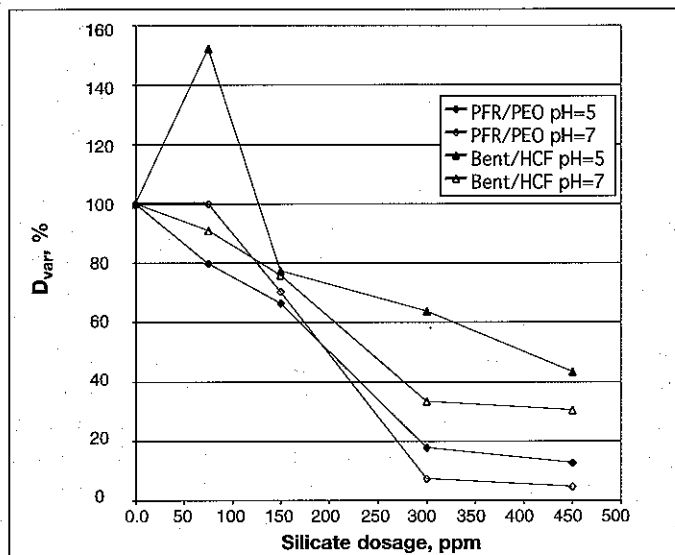


Fig. 9 Impact of added sodium silicate on the drainage of PFR/PEO and HCF/bentonite programs.

interferes with the adsorption of the platelet to the surface of solids or to its interaction with flocculant molecule.

Figures 8 and 9 present the effect of added polygalacturonic acid and sodium silicate, model compounds representing anionic trash materials generated during peroxide bleached of TMP pulps (17), on performance of PFR/PEO and HCF/bentonite programs at pH=5 and 7.

As we can see, both retention programs studied show significant reduction of activity in terms of drainage at increased levels of polygalacturonic acids and silicate. The highest dosage of polygalacturonic acid corresponded to a measured cationic demand of about  $600 \mu\text{Eq/L}$ . This observation is in contrast to earlier observations by Allen and coworkers (31,37) and Miyanishi (34). In our case, the study was limited to the range only slightly exceeding practical application dosages (PFR at 4kg/t and PEO at 0.7 kg/t). Most

significant performance differences between cationic polymers and PEO for contaminated systems were previously observed (31) when a dosage range of polymers (as active component) under investigation was extended up to 1% (10 kg/t). It is quite possible that PEO may still be beneficial at these high dosage rates when performance of cationic polymers would suffer due to over-cationization phenomenon. Although some over-dosing is most likely justified for Britt Jar studies due to their single pass character, significant dosage increase may skew results when polymers with significant structural and mechanistic differences are compared.

There is most likely less sensitivity to increased levels of contamination for PEO-based programs than for cationic flocculants but this difference may not be as large as it was previously suggested. There is still a significant argument

within the technical community regarding mechanisms of operation of cofactor-PEO programs. Pelton (41,42) Lindstrom (43,44), Stack (45) and Van den Ven (46) published their proposed mechanisms. All these mechanisms assume some sort of interaction between cofactor and PEO molecule that happens in the solution, or after initial formation of patches on the surface of agglomerated solids. Sensitivity of PEO-based programs may not be originating from the PEO molecule itself but from an impact of chemical environment on the cofactor, its degree of protonation, solubility, and adsorption to the solids or ability to form hydrogen bonding with PEO. Any observations may then be very system and contaminant specific and dependent on the chemistry of the co-factor used. It is possible that this could explain the lack of impact of cationic demand on the PEO program when kraft lignin was used as a model contaminant (34). As could be expected, cationic demand value at the same dosage of polygalacturonic acid and its negative impact on drainage was higher at pH=7 than at pH=5.

## CONCLUSIONS

When drawing conclusions based on results published in this paper it is important to remember that they compare sensitivity to contaminant concentration not absolute level of performance. Each of the investigated retention programs showed its own characteristic sensitivity to the presence of ionic species. Mechanism of flocculation operating for given retention programs determines the contribution of the following effects to sensitivity to ionic contamination:

- suppression of double layer at higher conductivity levels
- change in adsorption properties through changes in solubility and surface chemistry
- sheltering the dipolar attractive forces
- conformational changes of polymer in solution or adsorbed polymeric patch

Two programs that are often quoted as being robust to high and varying contamination levels showed significant sensitivity. Bentonite, in combination with cationic flocculant, slightly reduced the impact of simple ionic species but showed high sensitivity to presence of silicates, phosphates and anionic trash. The mechanism of bentonite operation, resembling inorganic, rigid flocculant as proposed in this paper, explains its behavior. PEO-

based programs showed low sensitivity to simple ionic salts but were affected by increasing cationic demand. This observation possibly reflects the impact on cofactor chemistry, its absorption on the furnish elements or its interaction with PEO molecules.

The effect of anions derived from the weak acids is less detrimental at lower pH as they loose their ionic charge. Silicates are always detrimental regardless of program.

From the practical point of view this paper indicates that every effort must be made to stabilize the wet end chemistry of paper machines. Surveying mill systems for sources of instability and addressing them will bring benefits of improved machine efficiency and product quality. Separation of water loops between pulp bleaching areas and paper machines, new effective pulp thickening equipment allowing for high consistency bleaching, and on-line control and monitoring techniques are the most important tools available in stabilization projects.

Understanding mechanisms of various programs may allow a reduction in their sensitivity through modification of their application strategy. For instance, changing the configuration of feeding points of a dual polymer program and adding a coagulant together with a high molecular flocculant often improves its performance at high conductivity levels.

## ACKNOWLEDGEMENTS

The authors would like to thank Mr. John Moodie for support and valuable discussions during this project and to Mrs. Beata Skowron for her participation in project design and relentlessly conducting thousands of experiments.

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# Pulp fibre drag coefficient

SHELDON I. GREEN

## SUMMARY

This paper describes experimental measurements of the hydrodynamics of individual softwood and hardwood pulp fibres. The macroscopic geometrical characteristics (length, diameter, wall thickness) of individual hardwood kraft and softwood kraft fibres have been measured. Under carefully controlled conditions, the gravitational settling velocity of the same fibres has also been determined. These different observations allow correlation of fibre settling velocity and drag coefficient with fibre geometry.

The creeping flow drag coefficient of hardwood fibres is on average significantly lower than predicted by Cox's theory, whereas softwood fibre drag coefficients are predicted well by the theory. The source of the differences between theory and experiment is not known, but may be the complex morphology of real fibres, relative to the uniform diameter fibres considered by the theory. The complex morphology and spatial density variations of real fibres may also be a major source of the substantial dispersion in drag coefficient between fibres.

These results may help predict the separation of different pulp fibres (e.g. by length, diameter, shape, density, orientation, & species) in hydrocyclones, given a knowledge of the flow field in the hydrocyclone.

### Keywords

Pulp fibre, drag coefficient, hydrocyclone, morphology, separation

## INTRODUCTION

The properties of paper are dependent on the structural characteristics of the wood fibres that comprise it. The cell wall thickness is one such important characteristic. In papermaking, fibres with thinner

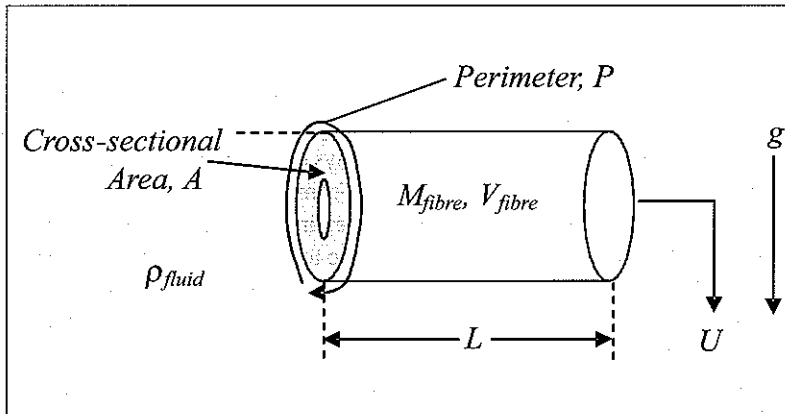


Fig. 1 Idealization of a pulp fibre settling in a fluid.

cell walls (earlywood) collapse readily into ribbons during sheet formation. Fibres with thicker cell walls (latewood) resist collapse and their smaller area of contact with other fibres means that they do not bond as strongly as fibres with thin cell walls. There is a strong desire in industry to separate pulp fibres with different properties depending on the properties desired of the finished product. One industrial approach for fractionating fibres is to use hydrocyclones (1,2). Previous experimental researchers (3,4) have shown that in a hydrocyclone the thicker-walled fibres preferentially migrate to the reject stream, and thinner-walled fibres move to the accept stream.

There have been efforts to model numerically the fibre motion in a hydrocyclone (5,6). The model involves first solving for the single-phase (pure water) flow in a hydrocyclone and then calculating the motion of 'mock fibres' in the single-phase flow. Such calculations have required an estimate of the hydrodynamic characteristics of individual wood fibres. For lack of better information, modelers assumed that wood fibres behave in the same way as cylinders or flexible linkages of spheres, using slender body theory for example (7,8). This estimation process is likely subject to substantial error, which can be avoided through direct measurement of the fibre hydrodynamics. The experimental measurement of the hydrodynamic characteristics of individual wood fibres is the topic of this paper.

The Reynolds number (based on diameter) of the flow around an individual pulp fibre is given by:

$$Re = \frac{\rho_{fluid} \cdot D_H \cdot U}{\mu} \quad [1]$$

where  $D_H$  is the fibre hydraulic diameter,  $\rho_{fluid}$  is the fluid density,  $U$  is the fibre velocity relative to the fluid, and  $\mu$  is the fluid viscosity (Figure 1). By convention  $D_H = 4AP$  where  $A$  is the average cross-sectional area of the fibre (including any partially full lumen) and  $P$  is its average perimeter. Typical Reynolds numbers of fibre flow in a hydrocyclone are in the range of 0.05 to 2, depending on the hydrocyclone characteristics, the exact location in the hydrocyclone, and the fibre characteristics (9). It can be noted that the hydraulic diameter, not the diameter of an idealized cylindrical fibre, is used in this definition. As will be explained later, the hydraulic diameter is used in this work, rather than the 'idealised' diameter used in previous work, because the hydraulic diameter is more consistent with what is known about the morphology of fibres in suspension. Specifically, fibre cross-sections have average aspect ratios of around 3 (e.g., see Figure 1 of reference 1), which is very different from a circle with its unit aspect ratio.

Other researchers have analytically and experimentally determined the drag on objects similar to pulp fibres. A rigid two-dimensional circular cylinder is similar to a pulp fibre. Cox (10) considered the creeping flow around a long slender solid body that may or may not be straight and developed a general theory to find the hydrodynamic force exerted on such body when it is placed with its axis perpendicular to a uniform flow.

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